An Experimental Evaluation of a Cooperative Communication-based Smart Metering Data Acquisition System

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***Abstract*—Smart meters are being deployed globally on a trial basis and are expected to enable remote reading and demand response among other advanced functions, by setting up a two-way communication network. However, it remains to be determined as to how these meters will transmit their data to an aggregation point. An elegant solution to this problem is the use of cooperative communication in a neighborhood area network. This work experimentally compares cooperative networks, deployed in disparate environments, in terms of range extension and energy consumption of the overall network. Data transmissions take place through the universal software radio peripheral (USRP) platforms. The method has been implemented in both indoor and outdoor environments, with cooperative transmission (CT) taking place over a multi-hop network, employing the binary phase shift keying (BPSK) scheme. The results indicate that CT can be used to effectively and reliably relay data in a network such as that in a smart grid.**

***Index Terms*—Cooperative communication, GNU Radio, synchronization, USRP, energy efficiency, network lifetime**

I. Introduction

The fifth generation (5G) wireless systems have recently attracted a lot of attention because of the many advantages they promise to offer. As 5G is a union of a variety of techniques ranging from algorithmic designs to system level designs, connecting billions of devices around the globe is a major challenge. The notion of 'connected anywhere and anytime' gives rise to many techniques and applications to be worked on; the internet of things (IoT) being the most prominent. Among the many applications of IoT, smart cities have recently captured the imagination of the research community. The prime motivation behind smart cities is to promote a healthy economy and sustainable growth, while ensuring a control over resources and the optimization of existing infrastructure. In literature, the concept of 'smartness' has been applied to a variety of contexts ranging from buildings [1] to the electric grid. However, this paper focuses on the development proposed in the electric grid using modern communication theory.

A *smart* grid is a self-healing network, which incorporates two-way digital communication technology to devices associated with the grid. While the exact framework of the smart grid currently being debated by the academia, [2] presented an elaborate information and communication technologies (ICT) architecture for smart grids. Moreover, each device in the network can be equipped with sensors for collecting data to be forwarded to the utility's network operations center. The smart meter is one such device.

The smart metering system allows continuous reading and recording of various quantities, such as power factor, in addition to the early-stage failure detection. This system is important for various purposes, including interval data, time-based demand data, time-based energy data (usage and production), service interruption, service restoration, quality of service monitoring, distribution network analysis, distribution planning, demand reduction and customer billing. Needless to say, the communication subsystem is a critical component of smart grid systems [3].

In literature, the most common candidates for communication in smart grids have been stated to be mobile phone networks using global system for mobile communications / general packet radio service / third generation / fourth generation technologies (GSM / GPRS / 3G / 4G), satellite communications, and licensed or unlicensed radio networks and power line communication (PLC) [4]. In this work, the authors have considered a smart metering system, in which individual nodes cooperate to establish radio links to deliver data. Henceforth, the term 'IoT device' has been used interchangeably with 'node' to describe an individual transmitting or receiving device in the network.

This paper has considered a smart metering system that uses cooperative communication to relay data in a multi-hop fashion to far-off aggregation points. Cooperative communication is a maturing area of research and is considered to be an important mechanism for efficient spectrum use. The cooperation between multiple IoT devices in a setup helps sustain network resources. In addition, cooperative transmission (CT) employs the concept of diversity to control the adverse effects of multipath fading. The inherent signal-to-noise ratio (SNR) advantage from CT may be used to increase the maximum distance to which data may be accurately received in a network, while reducing the individual transmission power from IoT devices.

The communication devices in most wireless sensor networks (WSNs) today have a limited battery life and transmit power. CT can be expected to be particularly suitable in such situations as it has been shown to achieve the same quality-of-service (QoS) at a lower transmit power at each node,

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as compared to single-input-single-output (SISO) networks. Moreover, CT is known to introduce ultra-reliability into the network, as the system continues to relay data even if an individual IoT device develops a fault. It is worthwhile to note that while previous work attempted to establish a one-dimensional network for data relay [5], and introduced a routing algorithm for relay node selection [6], we have considered a system involving multiple relay nodes concurrently transmitting data to other IoT devices.

Despite the many benefits of CT, the networks using this approach generally require synchronization among the relay nodes during transmission and reception. In literature, it has been seen that if timing errors are large enough, the system is deprived of the diversity gain advantage [13], causing poor performance. Similarly, if the sensors mounted on smart meters intend to transmit data using the aforementioned technique of CT, a trade-off between range, energy efficiency, and lifetime of the network needs to be analyzed. Simply put, increasing the range of operation requires a larger transmit power and hence result in lower energy efficient system with reduced lifetime. However, the role played by the surrounding environment, which may either be a line-of-sight (LoS) or a non line-of-sight (NLoS) setting, must be taken into account as well. Outdoor environments are generally referred to as LoS surroundings, whereas communication in NLoS channels is usually characterized by indoor propagations which are required when the networking area reduces to a home area network (HAN) [8] where smart devices in a home communicate with one another. Thus, a practical realization of various components of a smart city, especially in wireless communications regime, seems plausible under strict conditions.

The authors present herein an empirical proof of the range extension and increased energy efficiency and network lifetime seen in networks using CT. The SISO arrangement serves as a control, against which the operation of the cooperative networks have been compared. Each IoT device is basically a universal software radio peripheral (USRP) connected to general purpose personal computers (PCs). These PCs execute the modulation, demodulation and error rate determination stages in the GNU Radio environment. Additionally, the setup attains synchronization between multiple relay IoT devices by using stream tags in GNU Radio. These tags help realize a frequency division multiple access (FDMA) scheme for relay transmissions. The signals transmitted by the relay IoT devices undergo equal gain combining (EGC) at the destination node. All discussions yield the conclusion that CT can be used as an enabler wireless communications technique for smart metering, which is a component of future IoT design.

II. Related Work

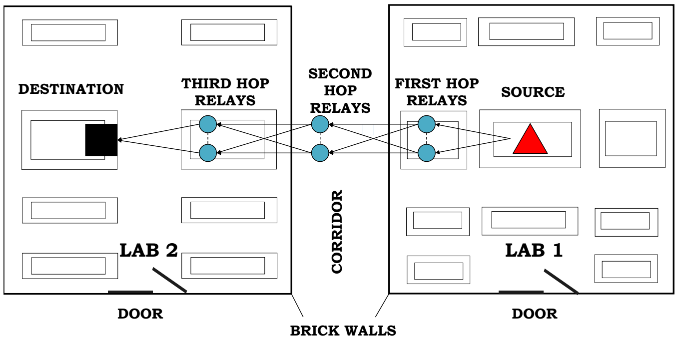
Considerable amount of work has been done to theoretically analyze cooperative multi-hop networks, e.g. [9] – [14] and the references therein. Theoretical aspects of energy efficiency in CT were discussed in [15]. In [16], the authors proposed a cooperative protocol for the establishment of transmitter and receive clusters, apart from data transmission. Additionally, [17] presents a mathematical model to address the situation arising from initial energy resources constraining the sum of the energy spent in a single sensor set.

Network lifetime is a key indicator of energy consumption as it serves as an upper bound for the utility of a sensor network. The network can only fulfill its purpose as long as it is considered 'alive'. It is, therefore, a metric for the maximum utility a sensor network can provide [18]. In view of the importance of this concept, [18] summarized all parameters that affect the lifetime of individual nodes as well as the overall network lifetime, apart from furnishing a formal definition of network lifetime that reflects all the characteristics of a typical sensor network. In [19], the authors put forth a single source broadcast strategy that was found to extend the life of a wireless ad hoc or sensor network by alternating between mutually exclusive sets of opportunistic large arrays (OLA) in two consecutive broadcasts.

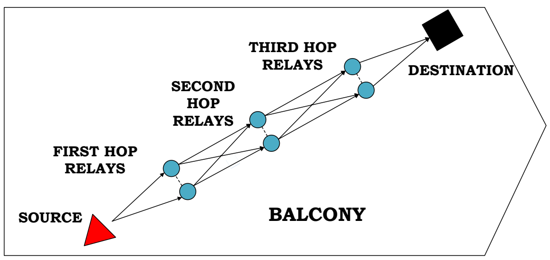
Although a lot has been done for theoretical analysis of CT, there are several instances in literature that implement synchronization in cooperative networks as well. For example, [21] implemented a timestamp methodology using *hardware synchronization*. The work considered a cooperative network in an indoor environment, with the test bed consisting of USRPs. It also investigated both single and multi-relay topologies while achieving signal combination through maximal ratio combining (MRC). As a further example, [22] outlined the adverse effects of timing errors on the quality of the signal received at the destination IoT device and attempted to correct them by timestamping. The resulting network was tested indoors using a two-hop and a ping pong experiment. The bit error rates (BERs) for the experiments at different transmit power is determined by keeping IoT devices at fixed positions in the setup. In addition, [23] demonstrated the advantages of cooperative communication in terms of range extension for a 2-hop cooperative network, whereas [24] implemented a medium access control (MAC) protocol for such networks. Both systems were tested in an indoor, office environment only.

All of the aforementioned papers stop short of implementing a truly multi-hop network where each hop represents an altogether unique location and where the number of hops is greater than two. In fact, [20] – [21] strictly adhered to a source-relay-destination topology. This paper, however,

- diversifies the testing environment to include outdoor surroundings,
- advances from the typical source-relay-destination setup to one that comprises multiple, successive levels of relays placed at physically independent positions,
- expands on the BER readings obtained from the network, to determine system performance in terms of range extension, energy efficiency and network lifetime,
- brings to fore the level of consistency in a cooperative network's results in disparate environments, and
- broadens the scope of performance analysis to include three parameters and investigates whether or not increased cooperation always has a positive relationship with coverage range, energy efficiency and network lifetime.



(a) Indoor Topology



(b) Outdoor Topology

Fig. 1: Topologies tested

III. System Model and Implementation

Fig. 1 shows the primary topologies used for the performance tests, which are explained in detail in the sections that follow. Each experiment comprised a source and a destination node, apart from other IoT devices, or relays, located between these two points. The relays employed the decode-and-forward (DF) scheme, while using BPSK modulation. The general form for BPSK is given by the expression,

$$s_n(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \pi(1-n)), n = 0, 1 \tag{1}$$

where E_b is the energy per bit, T_b denotes the bit duration and f_c is the frequency of the carrier wave.

The network was used to obtain the BERs at the destination node for a range of transmit powers. The tested systems consisted of one, two and three relays at each of the four network hops. Furthermore, each arrangement was tested for different source-destination (S-D) distances. It was also been ensured that the length of each individual hop is the same. It is worthwhile to remember that WSNs usually have a limited power supply. Therefore, there are chances that, over a course of time, individual IoT devices may run out of power and are, thus, unable to operate. This paper has defined *network lifetime* as the time taken for the first cooperating relay IoT device to be completely drained of power.

Fig. 2 demonstrates the various stages of signal processing in the transmitter and relay designs proposed by the authors. The network with a single relay per hop represents a multi-hop SISO topology. By extension, a cooperative network comprises multiple relays at the intermediate stage. A detailed explanation of several operational aspects may be found in the sub-sections that follow.

A. Transmitter Operations

The system has been designed to receive data in the form of an integer, float or character from the data source. The encoder can then convert this data into a packet of a payload length of 736 bits along with an access code of 64 bits. Access codes are helpful in determining the start of packets. Following modulation, the signal was transmitted from the USRP sink, which is the RF front end for transmission of radio signals.

B. Relay Operations

It is worthwhile to note that as the relay IoT device used the DF scheme, the part of the relay block diagram in Fig. 2 up to the decoder may be considered to be a receiver.

A higher sampling rate was used at the receiver, to allow this node to receive signals over a larger bandwidth. The USRP source served as the RF front end for receiving signals, digitizing them and sending them to the PC through the universal serial bus (USB) for processing. The purpose of the frequency translating filter was to move the incoming signals to the base-band, implement a low pass filter and downsample each stream to ensure that the sampling rate for each stream was the same as that employed for data transmission.

The next stage of signal processing involved the use of the frequency lock loop (FLL) to remove carrier frequency offsets. Subsequently, the timing recovery phase ensured that the symbols were sampled at the correct points through a matched filtering mechanism using a root raised cosine (RRC) filter. It also downsampled the complex data stream from 4 samples per symbol to 1 sample per symbol, before eliminating the channel phase distortions using the Costas loop.

The proposed network attained frequency diversity by combining the signal copies from each stream using EGC for signal combination. Following combination, the access code was removed, leaving the payload as the output. The network achieved transmit time synchronization by extracting a start of packet time using the stream tags provided in the GNU Radio application programming interface (API) and extrapolating this value using the total number of samples and the sampling rate.

C. Timing and Synchronization

The topologies for the cooperative networks considered in this research work, consisted of an individual source and a destination node. In contrast to the SISO arrangement, however, the intermediate stage of the cooperative network comprised various IoT devices, each receiving a signal from a disparate spatial path. It has been previously noted in literature that concurrent transmissions from the relays results in a high performance gain [21]. In the absence of measures to enforce timing and synchronization in the setup, it is unlikely that the relay IoT devices begin their respective transmissions simultaneously due to lags caused by PC scheduling and the subsequent data transfer from the PC to USRP. This loss in

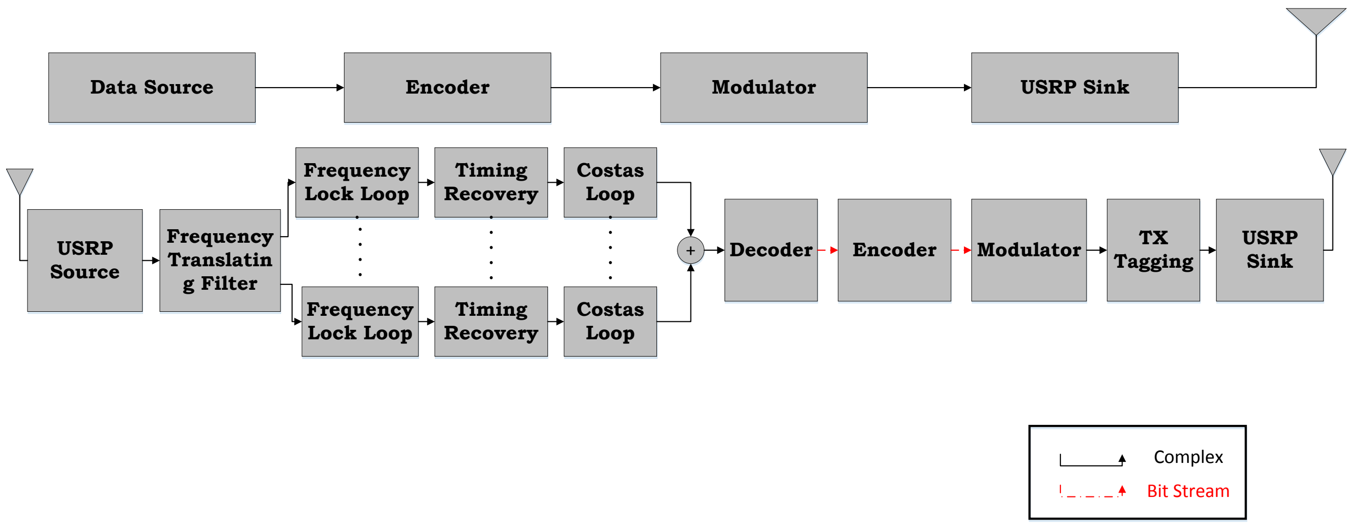


Fig. 2: Transceiver Design

synchronization, in turn, can result in a loss of diversity at the receiving IoT devices. It is noteworthy that the key role of the USRP is receiving, amplifying and transmitting the signal. Unlike the PC, it does not undertake any signal processing task.

The synchronization mechanism exploited two different stream tags, each of which denoted a unique piece of information. These include,

- rx–time: Generated once by the USRP Hardware Driver (UHD) block upon start of streaming.
- tx–time: The time-stamp that is compared with internal UHD clock for transmission.

The incoming messages were tagged at the start of signal reception. This *rx–time* tag carried a quantity with both integer and the fractional parts. A block developed in GNU Radio read this tag and obtained the timestamp. This value served as a starting point for tagging in later transmissions. This customized block had a single parameter as input, the delay, which was taken to be larger than the random delays at each IoT device.

The synchronization process was completed into two phases. The samples were first tagged with timestamps. This procedure is given by

$$\tau_{tx} = \frac{n}{R_{tx}} + d + \tau_{rx}, \tag{2}$$

where τ_{tx} is the value of the tx–time tag, n is the sample offset, R_{tx} is the sampling rate of the transmitting IoT device, d is a numerical value which is greater than the maximum delay of the PC and τ_{rx} is the value of the rx–time tag. The PC performed this tagging stage.

In the next step, these samples were stored by the USRP in its buffer, where they waited for the local timer to reach the value of their corresponding timestamps, indicating the beginning of transmission. This scheme was implemented for all relay IoT devices and the delay was adjusted so that the transmitting node overcomes the arbitrary delays caused by the PC. This achieves time-aligned transmissions.

Fig. 3 is a representation of the process explained above. In this figure, β_1 and β_2 are the random delays in packet transmission. Additionally, T_p is the deterministic duration of the source packet, N is the sample count of the source packet and T_s is the sampling period after downsampling. τ_{tx}, τ_{rx} and d have been discussed previously in this sub-section. It may be observed that d, mentioned in (2), is greater than both β_1 and β_2.

It is pertinent to mention that the synchronization algorithm introduced in this work disregards any portion of the incoming signal occurring before the start of packet. This extraneous segment at the start of reception was therefore 'sliced' off. In a 2-hop network, the entire procedure was performed at the destination, as it was the only IoT device in the network receiving multiple streams. Furthermore, the relays in a multi-hop network that removed the start of a stream had to compensate for this while determining the transmit time. This was achieved by counting at the relay device the number of samples skipped in reception, and adding that number to n in (2). This maintained the synchronization.

IV. Performance Evaluation

A. Experimental Setup

The arrangements for the tests are shown in Figs. 4-5. The tests were carried out on USRP B200 and N200 IoT devices, whose RF coverage falls in the range of 700 MHz to 6 GHz. The radios used in the experiments were equipped with VERT2450 antennas that have gains of 3 dBi. Each

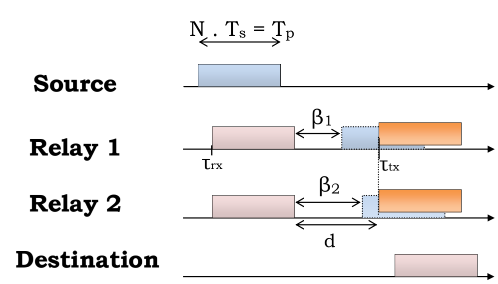


Fig. 3: Packet timing.

Fig. 4: Setup for a 3-relay cooperative network for indoor experiments.

TABLE I: Network Parameters

Parameter	Description
Modulation	BPSK
Source node frequency	2.6 GHz
1^{st} hop relay frequencies	2.8992-2.9008 GHz
2^{nd} hop relay frequencies	3.1992-3.2008 GHz
3^{rd} hop relay frequencies	2.9992-3.0008 GHz
Bit rate	50 kbps
Samples per symbol	4

reading was obtained after the source node had continuously transmitted data for 3 minutes. This meant that the destination received nearly 9 million bits in each test. All IoT devices in the network were connected to separate PCs that independently executed GNU Radio Companion (GRC) flow-graphs.

The indoor NLoS experiments were laid out in the following manner,

- the source and the first hop IoT devices were placed in Lab 1, which represents a typical indoor office environment,
- the second hop IoT devices were located in the adjoining corridor, where the brick wall results in an NLoS channel and introduced wall penetration losses,
- the third hop and the destination IoT devices were located in Lab 2, again with an NLoS channel.

The setup for indoor experiments is shown in Fig. 4.

Furthermore, the outdoor LoS experiments were conducted in a similar configuration on the first floor balcony of the campus faculty block. These schemes are illustrated in Fig. 5. While experimental details may be found in the subsections that follow, it is pertinent to state that in LoS experiments it was ensured that all the USRPs were placed at the same height from the ground. Additionally, the IoT devices were placed sufficiently high above the ground in order to prevent unwanted reflections. Throughout this paper, *NLoS channel* or *environment* have been used to refer to indoor tests, whereas *LoS channel* or *environment* denote outdoor experiments.

The testing campaign can be broken down into range extension and energy efficiency experiments, conducted in both indoor and outdoor environments. In each case, the BER at the destination was noted for a preset range of transmit powers.

B. Performance Evaluation in Terms of Range Extension

The first phase of experimentation involved increasing the S-D distance from 10m to 14m. The cooperative network consisted of a total of four hops for a given number of relays. The total transmit power for the entire network, as well as that for each hop, was kept constant. This measure was meant to keep all variables, except hop distance, constant to allow a fair assessment of the respective coverage ranges of multi-hop SISO and multi-hop cooperative networks. The relative coverage ranges for various network arrangements were determined from the transmit powers required to attain a given QoS at a fixed S-D distance.

C. Performance Evaluation in Terms of Network Energy Efficiency

The main purpose of these experiments was to determine whether CT can achieve energy efficiency by reducing the number of participating relay IoT devices, while maintaining a desired QoS in terms of BER. Two cooperative schemes were tested, namely completely cooperative networks (CCN) and limited participation (LP) networks. In CCN, all the relay IoT devices in every hop participated in the network while in LP, only a subset of the devices participated in transmitting the data to the destination. Both the CCN and LP networks were tested in indoor and outdoor environments to determine the effect of environment on the energy efficiency of the complete network for both schemes at a certain BER. These results were then used to determine which of CCN or LP schemes would be more energy efficient in a given environment and for a fixed QoS. The experiments using a multi-hop SISO network in LoS and NLoS environments acted as benchmarks for the CCN and LP tests.

For the purpose of these experiments, both the CCN and LP schemes comprised three intermediate relay hops and a final destination hop (a total of four hops). The distance between each successive hop was 3m. Therefore, the total distance between the source and destination IoT device was 12m. In

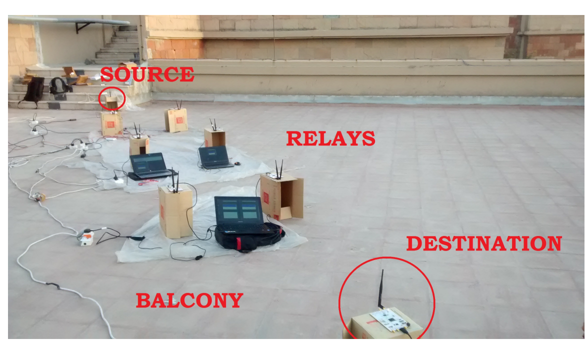


Fig. 5: Setup for a 2-relay cooperative network for outdoor experiments.

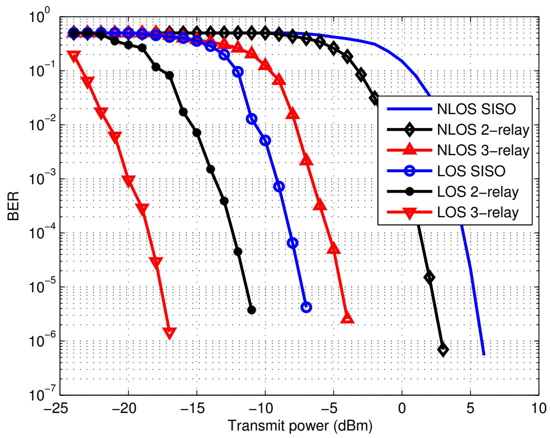


Fig. 6: BER comparison between multi-hop SISO and CT networks at a fixed S-D distance of 12m.

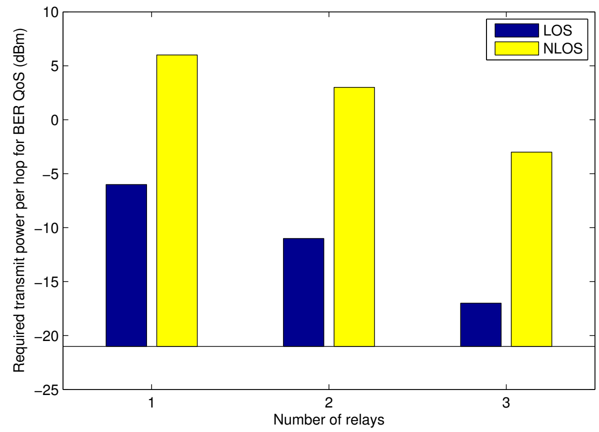


Fig. 8: Comparison of power requirements in LoS and NLoS channels for maintaining a BER of 10^{-4} at the destination in a 4-hop network with S-D distance of 14m.

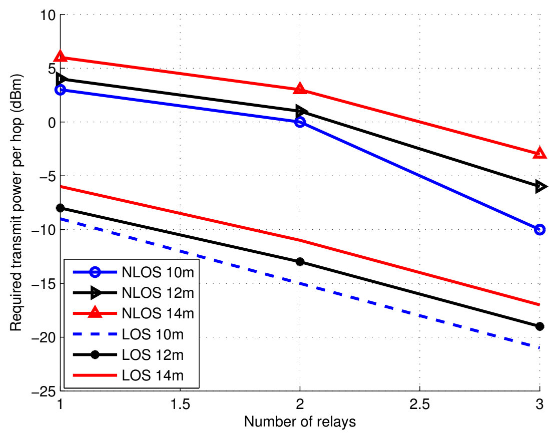


Fig. 7: Hop power requirement versus the number of relays per hop for ensuring a QoS of 10^{-4} at the destination.

the CCN network, 3 relay nodes per hop were used, while in the LP scheme only 2 relay nodes per hop were involved in the data transmission. Similarly, the SISO network only used a single node per hop over the same hop distance. Values of BER at the destination were obtained for a given range of transmit powers. Note that all IoT devices in the network were operating at the same transmit power for any given iteration.

D. *Performance Analysis*

Fig. 6 depicts the SNR advantage of transmissions taking place in a LoS environment. For example, SISO transmissions in this channel exhibit an advantage of nearly 12dB over transmissions in the NLoS environment at high transmit powers. An increase in the diversity order in both environments may also be seen for an increase in the number of relays per hop.

Fig. 7 is a plot of the node transmit powers required to maintain a QoS of 10^{-4} at the destination, versus the number of relays deployed at each hop, for varying distances in both LoS and NLoS channels. The first point to observe from the figure is the difference in powers required for each channel type to meet the BER criterion. The LoS channel needed much lower power for an equivalent number of relays and at the same distances than the NLoS channel, e.g. a SISO multi-hop network at a coverage distance of 14m required -6dBm power per hop in a LoS environment as compared to a hop power of 6dBm needed in NLoS environment to attain the same QoS. Additionally, it can be seen that the power requirement for different number of relays decreased at a faster rate in the NLoS channel when going from 2 to 3 relays per hop at a coverage range of 10m as compared to coverage distances of 12m and 14m, respectively. This dissimilarity in performance can be ascribed to the penetration losses inherent to the NLoS channel. The curves for the experiments conducted in the LoS channel demonstrate a linear trend, showing that diversity was achieved sooner in comparison to those for the NLoS experiments. It is worthwhile to observe from the figure that a 3-relay network in an NLoS channel at S-D distance of 12m required almost the same transmit power per hop as a SISO network in a LoS channel at a S-D distance of 14m.

Another scenario is the one in which the coverage distance was kept constant at 10m. Here it may be seen that the hop power requirement of a 3-relay network in an NLoS channel was -10dBm whereas a SISO network in LoS channel required hop power of -9dBm. It can, therefore, be seen that the hop power requirement of the SISO was greater and so was the individual node power requirement. Hence at a constant coverage distance, the SISO network in a LoS channel required greater hop power and has a reduced network lifetime as compared to the 3-relay network in an NLoS channel.

The bar graph in Fig. 8 illustrates the difference in performance of the network topologies in NLoS and LoS channels. The ordinate represents the transmit power required in each hop to maintain a BER QoS of 10^{-4} at a fixed coverage distance of 14m. The NLoS SISO topology required 6dB higher power than a LoS SISO topology, which amounts to a factor of 4. Similarly, 2-relay and 3-relay networks in an NLoS channel required 14dB additional power than the same networks in a LoS channel. This difference in power increased while moving from SISO to 2-relay networks, mainly due to the difference in diversities achieved by the cooperative networks in either channel.

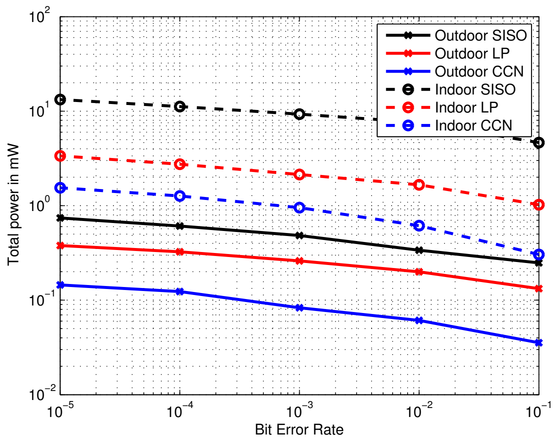


Fig. 9: Total power consumption versus BER for SISO, LP and CCN topologies.

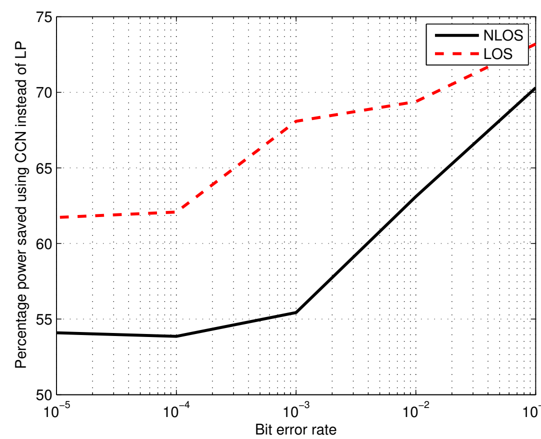


Fig. 10: Comparison of power saving between CCN and LP.

When moving from 2-relay to 3-relay network, it can be observed that the difference in power requirement for LoS and NLoS channels remained unchanged. This can be attributed to the increased redundancy in the indoor network, which allowed for greater diversity by overcoming challenges posed by the indoor scattering environments. The overall power requirement of the NLoS channel was still greater because of large penetration losses and the resulting reduced SNRs. However, the difference in powers did not increase as it did in the previous case.

Next, to study the energy efficiency of the complete network, the total power consumption of each network needed to achieve a certain QoS must be calculated. This was done by finding the individual transmit power (in mW) for each relay followed by taking the product of the power calculated and the number of transmitting IoT devices in each network. The number of transmitting nodes in the SISO network was 4 (1 source and 1 relay each in 3 hops), 7 in LP network (1 source and 2 relay IoT devices each in 3 hops) and 10 in CCN network (1 source and 3 relay IoT devices in 3 hops). Fig. 9 shows a plot of the total power required against a desired value of BER for each topology in each environment. It contains several points of interest. Firstly, the power required for achieving a certain BER value was higher in an NLoS environment as compared to the LoS environment. For example, to achieve a BER of 10^{-3} indoors, the CCN required a total transmit power of 0.953mW, while the outdoor SISO required 0.4842mW which is 49% less than the former case. Therefore, it can be seen that, for different environments, energy efficiency may be achieved by reducing the number of relays while achieving the same BER at the same distance.

Secondly, within the same environment, increasing the number of relays reduced the total power required to achieve a certain BER, clearly highlighting the advantage of cooperative communication. Specifically, CCN appeared to be more energy efficient at all values of BER as compared to LP. This comparison can be seen in Fig. 10, which plots the percentage of power saving if CCN was used instead of LP networks. In order to achieve an indoor BER of 10^{-1}, the CCN topology used 70% less power as compared to the LP network. This advantage reduces to 54% at a BER requirement of 10^{-5}, highlighting the fact that with an increase in the required BER, the advantage of CCN over LP diminished in both environments. This may be attributed to the fact that with an increase in the total power consumption of the network, the cooperation in an LP network became more efficient and LP networks could achieve the same QoS as that of CCN networks, hence becoming more energy efficient.

The results from the range extension and energy efficiency experiments will now be used to analyze how network lifetime varies in different networks and environments. The authors have defined network lifetime as the time of first node failure [18]. Since the USRPs used in the experiments are powered by the mains supply instead of batteries, hence the lifetime can be calculated using the transmit powers of the USRPs. This is because a higher power consumption would mean that an IoT device would use more energy and hence last for a lesser period of time on a limited power source. The authors have ignored the source node for this experiment, as it would limit the lifetime calculations of the entire cooperative network as well. This assumption is consistent with practical implementations of opportunistic networks where there is no dedicated transmitter. The network lifetime may be calculated by finding the transmit power used by a particular cluster of relays, converting it to mW and then dividing it by the number of relays in the particular cluster as shown in (3) and (4),

$$P_h(mW) = 10^{\frac{P_h(dBm)}{10}}, \tag{3}$$

$$P_i(mW) = \frac{P_h(mW)}{N_r}, \tag{4}$$

where P_h is the power radiated in a single hop, which is the sum of powers transmitted from all relays of that hop, P_i is the power of the individual IoT device and N_r represents the number of relays at each hop.

Since power transmitted is inversely proportional to the lifetime of the node (and, consequently, the network), the

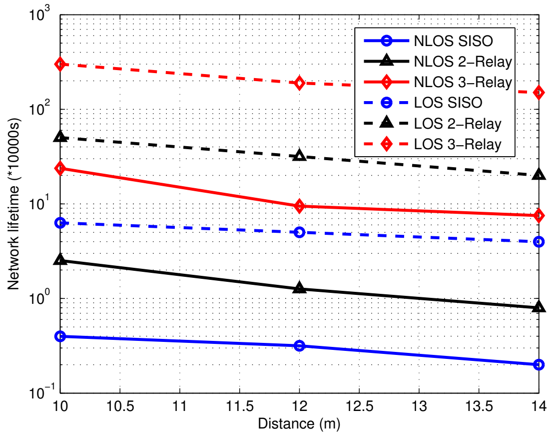


Fig. 11: Network lifetime versus coverage distance for varying number of relays for a QoS of 10^{-5}.

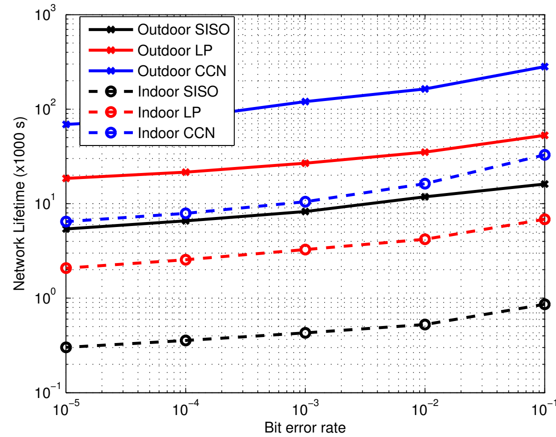


Fig. 12: Comparison of lifetimes across different BERs for SISO, LP and CCN.

network lifetime, η, is given as,

$$\eta = \frac{1000k}{P_i(mW)}, \quad (5)$$

where k is the constant of proportionality and $k = 1$ for plotting purposes.

Fig. 11 shows the relationship between network lifetime and coverage distance of the network at a BER QoS of 10^{-5}. The network lifetime has been measured in thousands of seconds, and the coverage distance in meters. From the graph, an inverse relationship between network lifetime and coverage distance can be seen, which is intuitive. Increased distances required greater transmit powers to maintain a QoS and hence resulted in a reduced lifetime. Another apparent conclusion is that increasing the number of relays in a hop, while keeping the overall hop power constant, also increased network lifetime. In the comparison between LoS and NLoS channels, however, it can be observed that the LoS SISO network had a higher lifetime than NLoS 2-relay network at the same range. This can be attributed to penetration losses and reduced diversity due to the scattering losses in the NLoS environment. In contrast, a 3-relay network in the NLoS channel exhibited a greater lifetime than a SISO network in the LoS channel did, because the added redundancy in the network allowed it to overcome the limitations of the NLoS channel.

Using (5), network lifetimes were calculated for each network topology in both LoS and NLoS environment, for different values of BER for energy efficiency experiments. The plot can be seen in Fig. 12. The trend for varying lifetimes against BER is similar to that of varying lifetimes against distance. As the required BER increased, the network lifetime decreased as the energy required at an individual IoT device increased. Similarly, it can be seen that, within the same environment, increasing the number of relays increased the network lifetime, indicating the benefit of CT. This is due to the fact that CT utilizes spatial diversity to improve the QoS at the receiver IoT device without raising the power requirement. In addition, it should be noted that CT is able to overcome the difference in environments, as the lifetime of the CCN

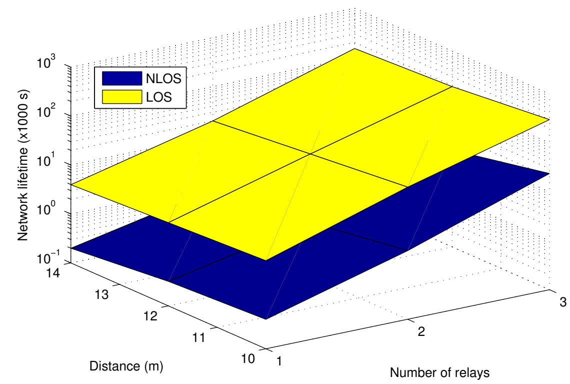


Fig. 13: Trade-offs between the number of cooperating relays, coverage distance and network lifetime.

network in an NLoS environment was better than that of a SISO network in a LoS environment across all BERs. This means that despite working in a rich scattering environment, CT is capable of providing LoS levels of performance, given sufficient relays per hop.

Fig. 13 summarizes the experiments and shows the relationship between network lifetime, range and the number of relays. It can be seen that as the coverage distance increased, the lifetime decreased, and as the number of relays increased, the lifetime of the network increased. The effect of the number of relays on lifetime was greater than the effect of distance, for the same BER.

It can hence be concluded that adding redundancy to the network can increase network lifetimes and coverage distances of a cooperative network at the cost of increased infrastructure. It can also be concluded that the channel plays a vital role in network deployment as seen in the previous graphs, where SISO networks in LoS channel performed better than 2-relay cooperative networks.

V. Conclusion & Future Work

This paper experimentally demonstrated the trade-offs between the range, network lifetime and energy efficiency of multi-hop cooperative networks in various operating environments. The results, presented herein, outlined various advantages of CT over SISO networks such as increased network range, prolonged network lifetime and reduced energy consumption. The paper also illustrated how varying the number of relays per hop can cause networks in different environments to show similar performances in terms of different parameters. Since the multi-hop cooperative networks in an NLoS environment performed similar to the multi-hop SISO networks in a LoS environment, it may be concluded that CT can overcome the limitations enforced by the channel and, hence, indoor sensor networks can greatly benefit from this technique. Since the IoT concept in general, and smart cities in particular would intrinsically require energy efficient communication from distributed sensors such as smart meters, CT may be considered a viable option for communication operations in such scenarios.

As a future extension to this work, the authors plan to test a wider array of network topologies in different settings. Furthermore, the authors plan to compute the LoS factor for a better characterization of the testing environments. In addition to observing the performance of relay nodes with varying and limited resources, the authors also intend to implement network coding to allow for multiple nodes to transmit data simultaneously in the absence of a dedicated source, thus obviating the need for additional channels.

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